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DURABILITY INVESTIGATION OF A ONE-QUARTER-SECTOR COMBUSTOR AT HIGH VALUES OF INLET-AIR PRESSURE AND TEMPERATURE

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DURABILITY INVESTIGATION OF A ONE-QUARTER-SECTOR COMBUSTOR AT HIGH VALUES OF INLET-AIR PRESSURE AND TEMPERATURE*

By Jerrold D. Wear

SUMMARY

The performance of an experimental one-quarter-sector annular combustor was determined at conditions of high inlet-air pressure and temperature. These conditions are representative of those that may be encountered in high-pressure-ratio turbojet engines during takeoff and low-altitude, high-speed flight. The combustor liner was comprised of channels that were overlapping in construction and independently supported. This type of construction was aimed at providing a structurally strong and relatively cool operating liner.

The inlet-air and combustor reference dynamic pressures were held at nominal values of 114 pounds per square inch and 50 pounds per square foot, respectively. An average exhaust-gas temperature of about 2000° F was maintained while the inlet temperature was varied from 900° to 1400° F. During approximately 21 hours of operation, the only structural failures occurred where two tabs (small flat pieces of metal attached to the support bolts that hold the channels) pulled away from the support bolts and permitted two channels to drop into the combustion zone. These two channels were burned and warped too badly for reuse; all other parts of the combustor remained in good condition. Better welding of the tabs to the support bolts may prevent this type of failure. Further increases in operating severity were obtained by gradually increasing the exhaust-gas temperature from 2000° to 2500° F. During approximately 20 hours of operation at these conditions, one tab failed and permitted two channels to hang into the combustion zone. There also was considerable warping of the channels on the short-radius side and warping of the pilot section. The channels on the long-radius side showed little or no effects from these tests. Increasing the exhaust-gas temperature from 2000° to 2500° F caused an increase in coke deposits in the pilot section that became heavy enough to disrupt the fuel spray pattern.

*Title, Unclassified.

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INTRODUCTION

High airflows per unit frontal area and high operating temperatures aid in achieving the decreased specific engine weight necessary for high flight speeds and altitudes. These conditions require engine components to function under greater mechanical and thermal stresses.

Previous investigations at the NASA Lewis laboratory demonstrated certain combustor design principles for operation at conditions representative of high-altitude, high-speed flight (refs. 1 and 2). Operating conditions resulted in combustor pressures between 2/3 and $1\frac{2}{3}$ atmospheres, outlet-gas temperature of about 2000° F, and inlet-air reference velocities as high as 200 feet per second.

Investigations reported in reference 3 showed that combustor liners similar to the types described in references 1 and 2 were not sufficiently durable to withstand the increased mechanical and thermal stresses imposed by conditions required at takeoff and low-altitude, high-speed flight. As shown by the data of reference 4, increasing the inlet-air temperature from 200° to 860° F (660° F increase) caused increases in liner metal temperatures varying from 1000° to 1550° F; the inlet-air pressure, reference velocity, and exhaust-gas average temperatures were held constant. The combustor failures reported in reference 3 led to a design that maintained satisfactory performance levels at high-altitude, high-speed flight conditions and, in addition, had good durability at the high-pressure, high-temperature condition. The liner parts were segmented in both axial and circumferential directions and were supported by the outer housing. Considerable cooling-air passage area through these segments was provided to maintain moderate metal temperatures. Individual pieces were allowed to expand freely to minimize stresses due to thermal gradients.

Results of an investigation to determine the structural durability of the best configuration described in reference 3 at more severe combustor pressures and temperatures are reported herein. Inlet-air and exhaust-gas temperatures were varied at constant values of combustor-inlet static and dynamic pressures. Other data are included to show a few (random) combustion efficiencies, exhaust temperature profiles, and pressure losses. Most of the data, however, are intended to indicate the structural condition and points of failure.

APPARATUS AND INSTRUMENTATION

Combustor and Installation

The combustor test section was connected to the laboratory air facilities as shown diagrammatically in figure 1. As described in reference 3, the inlet combustion air was heated by a counterflow tube heat exchanger.

At the airflow conditions required for the present program, however, the maximum air temperature that could be obtained was about 500° to 700° F below the values desired. Therefore, a direct-fired heater was installed in the inlet closure piece of the test combustor (fig. 2). Operation of this heater at various fuel-flow values, in conjunction with the heat exchanger, made it possible to obtain the desired combustion-air temperatures. All the air passed through the direct-fired heater, and the exhaust products and excess air were then fed directly to the test combustor. A punched plate containing 460 holes (1/4-in. diam.), which gave about 80 percent blockage of the pipe area, was located in the flange just upstream of the inlet transition (fig. 3) to smooth out irregularities in the air temperature and velocity profile. The air quantities were metered by an orifice plate installed according to ASME specifications.

The combustor housing (same one as described in ref. 3) and inlet and outlet ducting are shown in figure 3. The housing was a one-quarter sector of a single annular combustor with an outside diameter of $25\frac{1}{2}$ inches, an inside diameter of $10\frac{3}{4}$ inches, and a combustion length of about 23 inches. Other dimensions are given in figure 3. Inlet and outlet ducting simulated the airflow passage of a particular full-scale engine having an axial-flow compressor and turbine.

The combustor housing and exhaust-gas instrumentation section were immersed in a water bath (fig. 1) in which the water temperature was kept below the boiling point. This type of cooling, as compared with air-cooling, allowed a considerable reduction in weight and cost of these special shaped piping sections, since they were designed to withstand gas pressures of 450 pounds per square inch and gas temperatures of 2500° F. The exhaust instrumentation section (fig. 3) had a replaceable inner liner of 3/32-inch-thick Inconel metal, so that the exhaust-gas thermocouples would not "see" the cooled walls. The exhaust inner and outer annular converging sections of the housing were each covered with a replaceable liner or heat shield. These liners prevented the hot gases from impinging directly on the cooled walls (zone E, fig. 3).

Combustor Liner

The combustor liner used was essentially the same as the one designated configuration 20 in reference 3. A cutaway schematic of the type of construction is presented in figure 4, and a photograph of the liner in the housing is shown in figure 5 (looking upstream).

The inner and outer walls (short and long radius, respectively) of the liner were made up of individual parts designated as channels. Each channel was made up of short lengths welded together in an overlapping fashion with two longitudinal spacers between each length. This resulted in a step-strip type of construction. The channels were independently supported by the outer walls, as shown in figures 3 and 4 by three rows of bolts. Each channel was loosely held at each end and was not anchored to the pilot section or downstream heat shield. The mounting bolts were such that the radial distance between the inner and outer liner walls could be adjusted to desired values.

The main difference between configuration 20 and the combustor used for the current investigation was the pilot section (zone B, fig. 3). In configuration 20, the annular pilot section was composed of two one-eighth sectors bolted to the fuel manifold (fig. 11(a), ref. 3); three fuel nozzles were evenly spaced in each one-eighth sector. The new pilot section was a single one-quarter sector, in which six fuel nozzles were evenly spaced (fig. 5). The inner and outer walls of the pilot section were composed of overlapping segments welded to supports between each segment. All parts of the pilot section and the liner channels were made of 1/16-inch-thick Inconel metal.

Six duplex nozzles were used for fuel injection and are diagrammatically shown in figures 3 and 4. These nozzles were designed to provide an atomized spray over the complete range of fuel flows required. Each nozzle had both small- and large-slot systems. The small slots gave good atomization at low values of fuel flow; the large slots permitted high flows at moderate values of fuel pressure. The fuel manifold was split into two passages so that the small-slot and large-slot systems of the nozzles were fed fuel independently, but each nozzle slot system did not receive fuel independently of the other nozzles (zone A, fig. 3).

Instrumentation

The combustor instrumentation stations are shown in figure 3. The inlet-air temperature was measured at station 1 by four closed-end Chromel-Alumel thermocouples. Location of the temperature- and pressure-measuring devices in the inlet ducting is shown in figure 6. Inlet velocity pressures were measured at the same station with five rakes, each having four total-pressure tubes. The tubes were connected to strain gages that were balanced by wall static-pressure taps at station 1. Velocity pressure readings from the strain gages were recorded on a strip-chart recorder. The wall static taps were also connected to strain gages that were connected to automatic balancing potentiometers.

Combustor-outlet temperatures and pressures were measured at station 2 with a polar-coordinate traversing-probe mechanism that made five circumferential sweeps at radial centers of equal areas. The locations of these sweeps are shown in figure 7. A similar probe mechanism is described in reference 5. The probe had two measuring elements: a sonic aspirating-type platinum-13% rhodium - platinum thermocouple and a total-pressure tube. A strain gage indicated the difference between the total pressure sensed at the probe end and the total pressure measured at the combustor inlet; the difference was considered to be the total-pressure drop across the combustor system. An X-Y automatic-balancing potentiometer recorded a continuous trace of the temperatures and pressure drop during circumferential motion of the probe. A photograph of the probe sensing-head detail is shown in figure 5 of reference 3.

Fuel

The fuel used in the investigation was MIL-F-5624C, grade JP-5 (NACA 56-66). Some physical and chemical properties of the fuel are presented in table I.

PROCEDURE

Data were taken at the nominal combustor test conditions given in table II. Inlet-air reference velocities and dynamic pressures are based on the maximum cross-sectional area of the combustor housing (B-B, fig. 3) and on combustor inlet-air density (calculated from inlet total pressure).

Inlet condition A corresponds approximately to an engine with a pressure ratio of 8 at Mach 2.5 and 35,000 feet. The severity was then effectively increased by increases in inlet-air and exhaust-gas temperatures.

The various test conditions were used in the same order as given in table II. A minimum run time of 2 hours was arbitrarily used for the test conditions; however, when possible, the combustor was operated for longer periods of time. For example, the combustor was operated at the first condition (A) for a period of 2 hours. The combustor liner was then examined to determine if any failure occurred. If the liner condition was good, the next condition was used. In some cases when there was a small failure, the part was repaired or replaced; and the combustor was then operated at the next condition. The combustor was operated at each condition for periods from 2 to 4 hours.

Combustor total-pressure losses, outlet temperature profiles, and combustion efficiencies were determined at a few of the conditions. The large amounts of soot or smoke in the exhaust gases would sometimes plug the sonic probe before complete data were taken. Also, in some cases, very high local exhaust-gas temperatures (>3100° F) caused probe failure before all data were obtained. Because of this possibility of probe failure at some of the conditions, the fuel flow necessary for the desired average exhaust temperature was calculated from an assumed combustion efficiency of 97 percent and the desired inlet and exhaust temperatures.

Combustion efficiency, when computed, was calculated as the ratio of the measured enthalpy rise from inlet to outlet instrumentation planes to the enthalpy added by the fuel. The outlet-gas enthalpy was determined, when possible, from the average outlet-gas temperature, which was obtained from the circumferential traces at each of the five radii. Values at 2° intervals on the circumferential traces, or a total of 215 temperatures, were averaged for each data point.

The combustion inlet air was heated to approximately 700° F by the heat exchanger (fig. 1) for all the tests. The direct-fired heater (fig. 2) was then operated to bring the temperature on up to the desired values, which required increases from 200° to 700° F. The combustion efficiency of the direct-fired heater varied from about 97 to 100 percent. Assuming complete combustion, the following table gives the calculated gas composition (percent by volume) entering the test combustor at three different conditions:

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Temperature increase added by direct-fired heater, °F	Composition of gases entering test chamber, percent			
	Oxygen	Nitrogen and inerts	Carbon dioxide	Water vapor
0	20.95	79.02	0.03	--
200	19.93	78.87	.61	0.59
700	17.79	78.16	2.06	1.99

To determine whether this change in composition would greatly affect the calculated combustion efficiency of the test combustor, a sample set of data was calculated twice by assuming minimum and maximum contamination. The assumption of maximum contamination caused the calculated efficiency to change from 98 to 101 percent. Because the effect was small, and also since durability considerations were the main object of the test program, all combustion-efficiency calculations were made with zero contamination assumed.

RESULTS AND DISCUSSION

Results of tests at high inlet-air pressure and temperature on the structural durability of a one-quarter-sector annular combustor are presented in this section. Additional data on other performance characteristics are also shown. The durability results include several photographs of the liner - with coke deposits - in the combustor housing (looking upstream toward the fuel nozzles) and remarks about the physical condition of the combustor after operation at the several inlet conditions. Limited performance data are presented in table III and in several graphs.

Structural Durability

The condition of the liner parts at the beginning of the tests is shown in figure 5. The pilot section had not been previously used. However, all the channels had been used to obtain data reported in reference 3 (approx. 20 hours of operation at conditions similar to condition A - 725° air temperature instead of 900° F).

In the following discussion, only the values of inlet-air temperature, intended average exhaust temperature, and run time are given with the discussion of any particular inlet condition. The order of these variables for each inlet condition is the same as that given in detail for condition A.

Inlet-condition A. -

Inlet-air temperature, °F 900

Intended average exhaust temperature, °F 2000

Run time at condition, hr:min 2:00

The condition of the channels and pilot section was good; no cracks or warping were observed. There was some coke buildup on the nozzle protector plate (fig. 4) between the nozzles nearest the walls. No cleaning or changes were made for operation at the next condition.

Information from reference 3 indicated that operation at a condition similar to A was generally coke-free. In some cases formations 1/16- to 1/8-inch thick would form on the nozzle plate but none on the pilot-section walls or the channels.

Inlet-condition B. - 1000; 2000; 3:55

The channels were in good condition, although some of the tabs (small flat pieces of metal attached to the support bolts that hold the channels, fig. 5) were warped somewhat. The flat sides of the pilot section were warped inwards a small amount. There was considerable more coke on the nozzle plate near the ends. No cleaning or changes were made.

Inlet-condition C. - 1100; 2000; 3:45

The combustor had been operated at the test condition for about $3\frac{1}{2}$ hours when there was a decrease in the pressure drop across the combustor.

A temperature-pressure survey was started, and about halfway through the second radius (fig. 7) the gas temperature increased sharply to above 3100° F and the thermocouple failed. The test was stopped, and inspection showed one zone-C channel (fig. 3) hanging down into the combustion area and a zone-D channel gone altogether. Both were from the short-radius side or inner wall. Photographs taken of the liner (fig. 8) show that the tabs had come off two of the support bolts. The failed tabs, which had been welded to the bolts, looked as if the metal had torn away from around the weld instead of the weld failing. The other channels seemed in good condition. Some of the welds holding the pilot-section steps had broken, and the steps were warped. The amount of coke on the nozzle plate was smaller than at the beginning of the test. E-424

Since other tabs (0.031-inch-thick Inconel metal) showed some warping, all were removed from the support bolts and replaced with tabs made from 0.043-inch-thick Inconel metal.

Two new channels were installed, the welds were repaired on the pilot section, and most of the coke was removed.

Inlet-condition D. - 1200; 2000; 3:00

Channels and pilot-section steps were in good condition; however, the flat (originally) sides of the pilot section were warped more than before. There was a considerable amount of coke at the ends of the nozzle plate. No cleaning or changes were made.

Inlet-condition E. - 1300; 2000; 4:00

Channels and pilot section appeared to be in good condition. There was a large amount of coke on the nozzle plate around the nozzle on the left side (looking upstream). No cleaning or changes were made.

Inlet-condition F. - 1400; 2000; 4:00

A photograph (fig. 9) was taken of the liner after operation at condition F. There were no warped channels or broken tabs, although some welds on the side of one channel (center of long radius, zone C) had broken. There was considerable warping of some of the pilot-section steps, and the sides were warped inwards more than before. Comparison of figure 9 with figures 5 and 8 show more space between pilot section and channels at both the short- and long-radius sides. There was a large amount of coke on the nozzle plate around the nozzle on the left side.

The pilot-section steps and sides were straightened, steps of the one channel were rewelded, the spacing between the pilot section and channels was adjusted to original values, and the coke was cleaned out.

Conditions A to F consist of nominal exhaust-gas temperature of 2000° F, while the inlet-air temperature was increased from 900° to

1400° F. Conditions G through J are at a constant inlet temperature of 1200° F, while the exhaust-gas temperature was increased from 2200° to 2500° F.

Inlet-condition G. - 1200; 2200; 3:30

Channels and pilot section appeared to be in good condition. Part of the nozzle plate between the two left-hand nozzles had burned away. The coke deposits on the plate were small. No cleaning or changes were made.

The low-deposit result was inconsistent with results of the other tests, although a higher exhaust-gas temperature had been used. In order to determine if the value was peculiar to the condition or perhaps the coke formation had broken away just before shutdown, the condition was repeated.

Inlet-condition G. - 1200; 2200; 3:15

The pressure drop across the combustor decreased suddenly after about 3 hours of operation. A temperature-pressure survey was started; about halfway through the first radius there was a rapid increase in temperature to above 3100° F (recording instrument maximum), and the thermocouple failed. Inspection after shutdown showed that a tab had come off a support bolt in the middle row of the short-radius side and permitted both C- and D-zone channels to hang down into the gas stream. Both were burned too badly for reuse.

There was a large amount of coke on the nozzle plate; this indicated that probably during the first test the coke deposits had broken away just before the test was stopped.

The two channels were replaced with ones that had been previously used, and a new support bolt was installed. The coke was cleaned out of the pilot section, and some slightly warped steps were straightened.

Inlet-condition H. - 1200; 2300; 3:00

A photograph (fig. 10) was taken of the liner after operation at condition H. The coke formation was heavier than it had been for any of the previous conditions. It had bridged over several of the nozzles. The burned hole in the nozzle plate had enlarged enough to reach the nozzle hole. The pilot section had a weld broken on one of the steps. A zone-D channel, short radius second from right, had bent or sagged a small amount. The failure had taken place on a flat part of the channel at the end of the bent-over side pieces (the channel cross section changes from a U-shape to flat). The channel was straightened, the pilot-section step was rewelded, and the coke was cleaned out. A new nozzle protector plate was installed.

Inlet-condition I. - 1200; 2400; 4:30

The combustor was operated at the test condition for about $1\frac{1}{4}$ hours and then shut down because of electrical power failure. Channels and pilot section appeared to be in good condition; there was a large formation of coke near the center of the nozzle plate. This was removed, and only a small amount remained on the plate.

The combustor was then operated at the same conditions for an additional $3\frac{1}{4}$ hours. The coke deposits on the nozzle plate were larger than those shown in figure 10. There were no bent or warped channels, although the right side of the pilot section was warped inwards a considerable amount. The large coke formations were removed; no other changes were made.

Inlet-condition J. - 1200; 2500; 3:15

A photograph of the liner is shown in figure 11. There was a large amount of coke on the nozzle plate; some of it extended downstream nearly to the end of the pilot section. A sagging or bend in a zone-D channel, short radius, can be seen. This failure occurred, as before, on a flat section of the channel. The middle two channels were bent more than the outer two. It can also be seen that some of the tabs were bent a considerable amount. The channels on the long-radius side appeared generally to be in good condition. Some of the channels in zone C had steps that were raised or warped somewhat. The space between the pilot section and channels had increased from the original spacing. Two of the steps in the pilot section were warped.

All the channels on the short-radius side were straightened, and the one that had bent or warped the most was replaced with a new one. The pilot-section steps were straightened, and the spacing with the channels was adjusted to the original spacing. All the coke was cleaned out of the pilot section.

Since the coke deposits always seemed to have started buildup on the nozzle plate, it was removed for the next test. The nozzles were about 1/4 inch behind the plate, which kept the nozzle face or tip out of the combustion zone. With the plate removed, however, about 3/4 inch of the nozzle body extended into the combustion zone.

Inlet-condition K. - 1400; 2500; 3:00

A photograph of the liner is shown in figure 12. There were no broken tabs or channels. However, all four short-radius channels (zone D) were bent or sagged down. The coke deposits completely filled the back of the pilot section and were bridged over all the nozzles. One formation extended out past the pilot section. Except for a small amount of warping of some of the steps, the long-radius channels were in good condition. Figure 12(c) shows the pilot section with the coke removed. There was a considerable amount of warpage of some of the pilot-section steps. The coke deposits adhered to the pilot section much more securely than when the nozzle plate was installed.

Performance Characteristics

A few data on temperature profiles, combustor pressure drop, and combustion efficiencies are given in table III.

Temperature profiles. - Figure 13 is a plot of exhaust-temperature profiles or patterns obtained during operation at conditions C and F. Also shown is the average of any one profile plotted against its distance from the inner wall or short-radius side of the exhaust instrumentation section. The location of the profiles or probe paths is shown in figure 7.

The combustor had been operated for about 7 hours (conditions A, B, and part of C) when the data of figure 13(a) were obtained. The average temperature for this run was 1857° F (desired 2000° F) with a maximum of 2260° F recorded. It appears that some warping had taken place, permitting an increase of dilution air near the center of the short-radius side. As described previously, it was during operation at this condition that two right-center short-radius channels had come loose (fig. 8). It is possible that some failure had already taken place when the data were taken.

Coke was cleaned from the combustor, and the damaged parts were replaced. The data of figure 13(b) was obtained after about 13 more hours of operation (conditions D, E, and part of F). An average exhaust-gas temperature of 2031° F was obtained (desired 2000° F) with a maximum recorded temperature of 2410° F. The sharp decrease in temperature of the number 1 profile at 20° right (probe sweep) indicates an increase in dilution air along this path rather than a blocked fuel nozzle. All profiles would be affected by nozzle blockage.

The plots of profile average temperatures show that those of profile 1 (short radius) are about 225° F higher than those of profile 5 (long radius). Peak variations were as much as 550° F. This may indicate why more warpage and all tab failures occurred on the short-radius side.

Figure 14 is a plot of profile-1 exhaust temperatures obtained at five different conditions. The data at conditions A and C were reasonably symmetrical. However, the profiles get progressively worse at conditions F, G, and H. For example, temperatures obtained at condition H varied from 2800° F at 20° probe-sweep left to 1800° F at 25° probe-sweep right.

Combustor total-pressure loss. - The pressure-loss values in table III are similar to those given in reference 3 for comparable operating conditions. For the type of test reported herein, the actual values are probably not as important as variations in the readings that can indicate some type of liner failure.

Combustion efficiency. - Combustion efficiencies should be approximately 100 percent because of the high inlet-air pressure and temperatures unless the liner and/or the pilot section were severely warped or destroyed. Efficiency calculations of data obtained at conditions C and F give values of 101.3 and 101.5 percent, respectively.

CONCLUSIONS

A previous investigation with an experimental combustor that was operated for approximately 20 hours at high inlet-air temperatures and flows common to supersonic engine conditions showed no major structural failure, although four different tabs holding the channels to the support bolts failed. Thicker tabs or better welding of the tabs to the support bolts should eliminate such failures. For the investigations reported herein, this same combustor with a modified pilot section was operated at more severe conditions by successive increases in inlet-air and exhaust-gas temperatures. A total run time of 41 hours, 10 minutes was accumulated during the investigation.

The structural failures encountered during the test program were:

1. Loss of tabs holding channels to the support bolts.

a. All tab losses occurred on the short-radius side and, except for one case, were from the center row (circumferentially) of support bolts.

b. The temperature profile plots indicate that the temperatures of the short-radius tabs and channels were possibly, in some cases, 200° F higher than those on the long-radius side.

c. These results indicate that it is necessary to improve the structural integrity of the tabs or the method of supporting the channels.

2. Warpage of channel members at points where the channel cross section changed from a true channel cross section to a flat shape. This change in shape occurred at the "steps" where adjacent parts overlapped.

a. This warpage occurred to channels on the short-radius side. In general, all the long-radius channels were in good condition.

b. A redesign of the channels so as to have a longer length of channel-shaped cross section would probably prevent the warpage.

3. Warpage of the pilot section.

a. The one-piece one-quarter-sector pilot section had a considerable number of broken step welds and warpage of the side pieces. These caused misalinement between the pilot section and the channels.

b. A redesign of the pilot section permitting more freedom of movement of the parts would help to prevent warpage due to local heating.

The pilot section of this combustor was substantially free of coke after several hours of operation at a condition similar to inlet-condition A (725° F instead of 900° F). As the inlet temperature was increased to 1400° F (2000° F exhaust-gas temperature), the coke deposits increased somewhat.

However, as the exhaust-gas temperature was increased to 2500° F, the coke deposits increased far beyond a tolerable level. For operation at these conditions, the pilot section would have to be redesigned in order to decrease the coke deposits.

Combustor total-pressure-loss and combustion-efficiency values obtained were comparable with the values reported for the previous experimental combustor.

A combustor total-pressure loss (this value not used for calculations) was continuously monitored during operation. This made it possible to determine when some part of the liner failed. For example, the loss of a channel would cause enough change in pressure drop to be noticeable. However, misalinement of parts due to warpage had small effect on the pressure drop.

The combustor configuration described herein may be far from optimum insofar as durability and coking at the more severe operating conditions are concerned. Additional development work could conceivably result in significant improvements in these performance characteristics. It appears that the liner construction techniques employed herein (an articulated structure divided into many small segments in both the circumferential and longitudinal directions, with all parts supported from the combustor housing) show considerable promise. These techniques provided greater structural strength and cooler operation than for liners previously used. This type of construction permitted operation at conditions that would cause failure of conventional-type liners in a very short period of operation.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, April 21, 1960

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TABLE I. - PROPERTIES OF MIL-F-5624C,

GRADE JP-5 (NACA 56-66) FUEL

ASTM Distillation, D86-52	
Initial boiling point, °F	336
Percentage evaporated, °F	
10	368
30	389
50	411
70	438
90	475
Final boiling point, °F	512
Residue, percent	1.2
Loss, percent	0
Specific gravity, 60°/60° F	.810
Hydrogen-carbon weight ratio	.161
Net heat of combustion, Btu/lb	18,600
Aniline point, °F	146.3
Freezing point, °F	-50

TABLE II. - NOMINAL COMBUSTOR TEST CONDITIONS

[Inlet-air total pressure, 114.3 lb/sq in. abs; inlet-air reference dynamic pressure, 50 lb/sq ft.]

Test condition	Inlet-air temperature, °F	Airflow, lb/sec	Inlet-air reference velocity, ft/sec	Average exhaust-gas temperature, °F
A	900	19.71	119	2000
B	1000	19.02	123	
C	1100	18.40	128	
D	1200	17.84	132	
E	1300	17.32	135	
F	1400	16.85	139	
G	1200	17.84	132	2200
H				2300
I				2400
J				2500
K	1400	16.85	139	2500

TABLE III. - COMBUSTOR TEST CONDITIONS AND PERFORMANCE DATA

Test condition	Inlet-air total pressure, lb/sq in. abs	Inlet-air temperature, °F	Air-flow, lb/sec	Inlet-air reference velocity, ft/sec	Inlet-air reference dynamic pressure, lb/sq ft	Overall exhaust average temperature, °F	Fuel-air ratio	Combustion efficiency, percent	Total-pressure loss, percent	Individual probe data		
										Probe path (fig. 7)	Exhaust average temperature, °F	Maximum temperature, °F
C	114.40	1107	18.72	130	51.8	1857	0.01169	101.3	3.3	1	1857	2110
										2	1988	2210
										3	1942	2090
										4	1853	2260
										5	1646	1790
F	114.22	1387	16.99	140	50.9	2031	0.01028	101.5	3.1	1	2055	2250
										2	2156	2410
										3	2116	2510
										4	2019	2400
										5	1807	1995
A	114.42	886	19.94	119	50.5	--	0.01343	--	--	1	1807	2130
G	114.35	1205	17.74	131	49.5	--	.01581	--	--	1	2098	2500
H	114.31	1200	18.14	134	51.9	--	.01701	--	--	1	2238	2800
Isothermal flow												
A	114.27	902	19.82	120	50.7	--	---	--	2.7	-	--	--
B		997	19.07	123	49.8	--	---	--	2.8	-	--	--
C		1102	18.47	128	50.3	--	---	--	2.9	-	--	--
D		1195	17.92	132	50.5	--	---	--	2.9	-	--	--
E		1300	17.30	135	49.7	--	---	--	2.8	-	--	--
F		1412	16.91	141	50.9	--	---	--	2.9	-	--	--

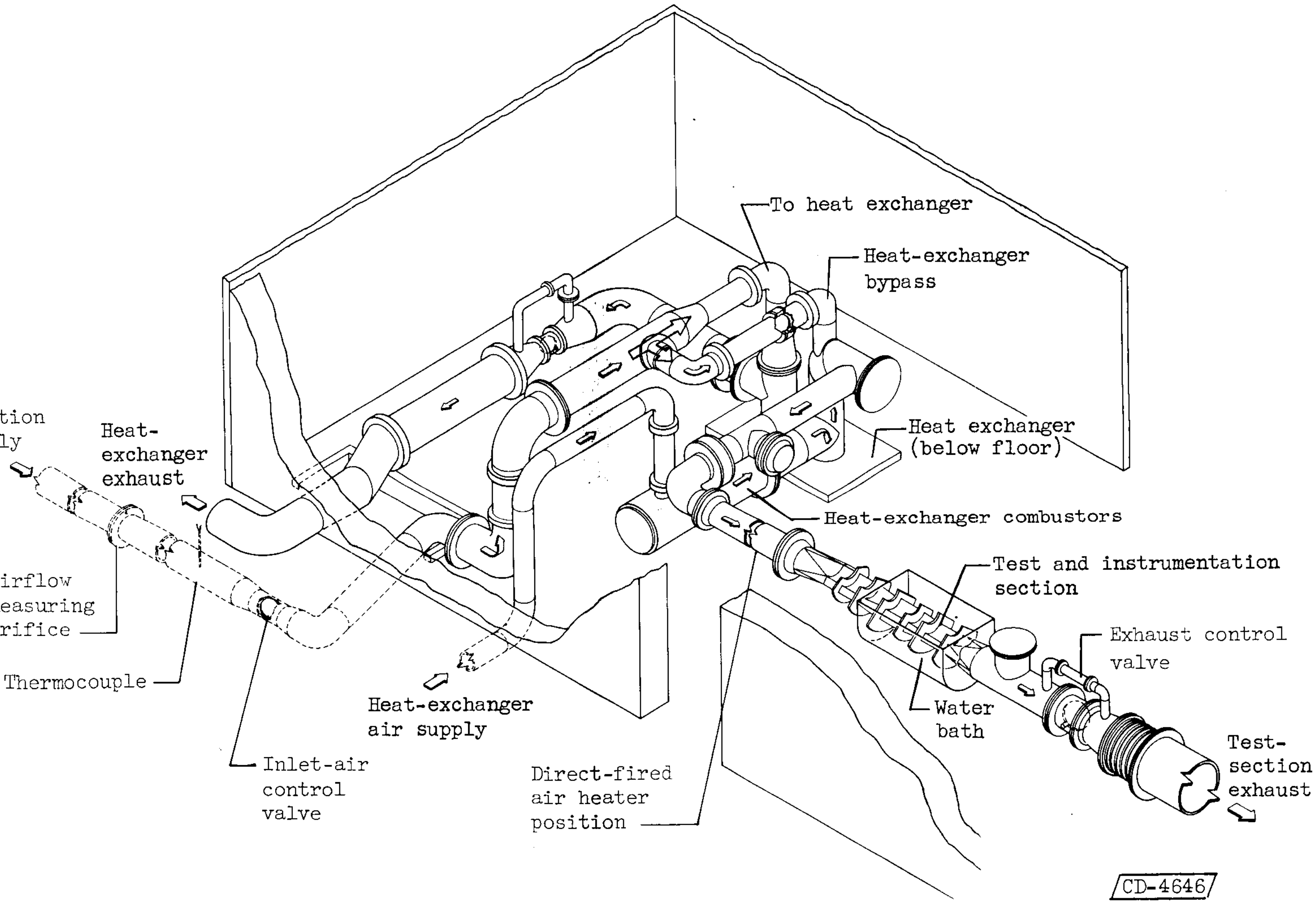

Figure 1. - Test installation.

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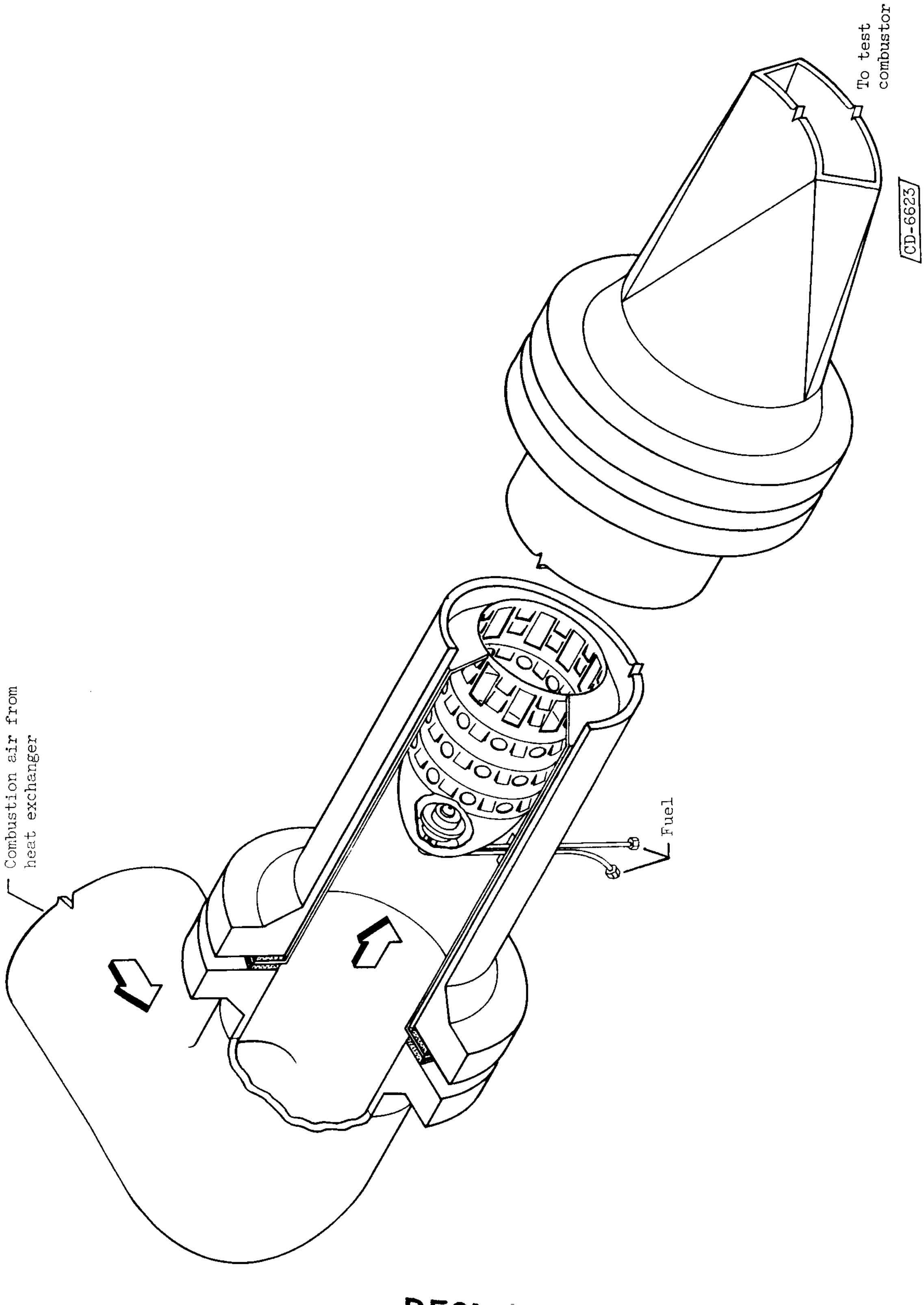
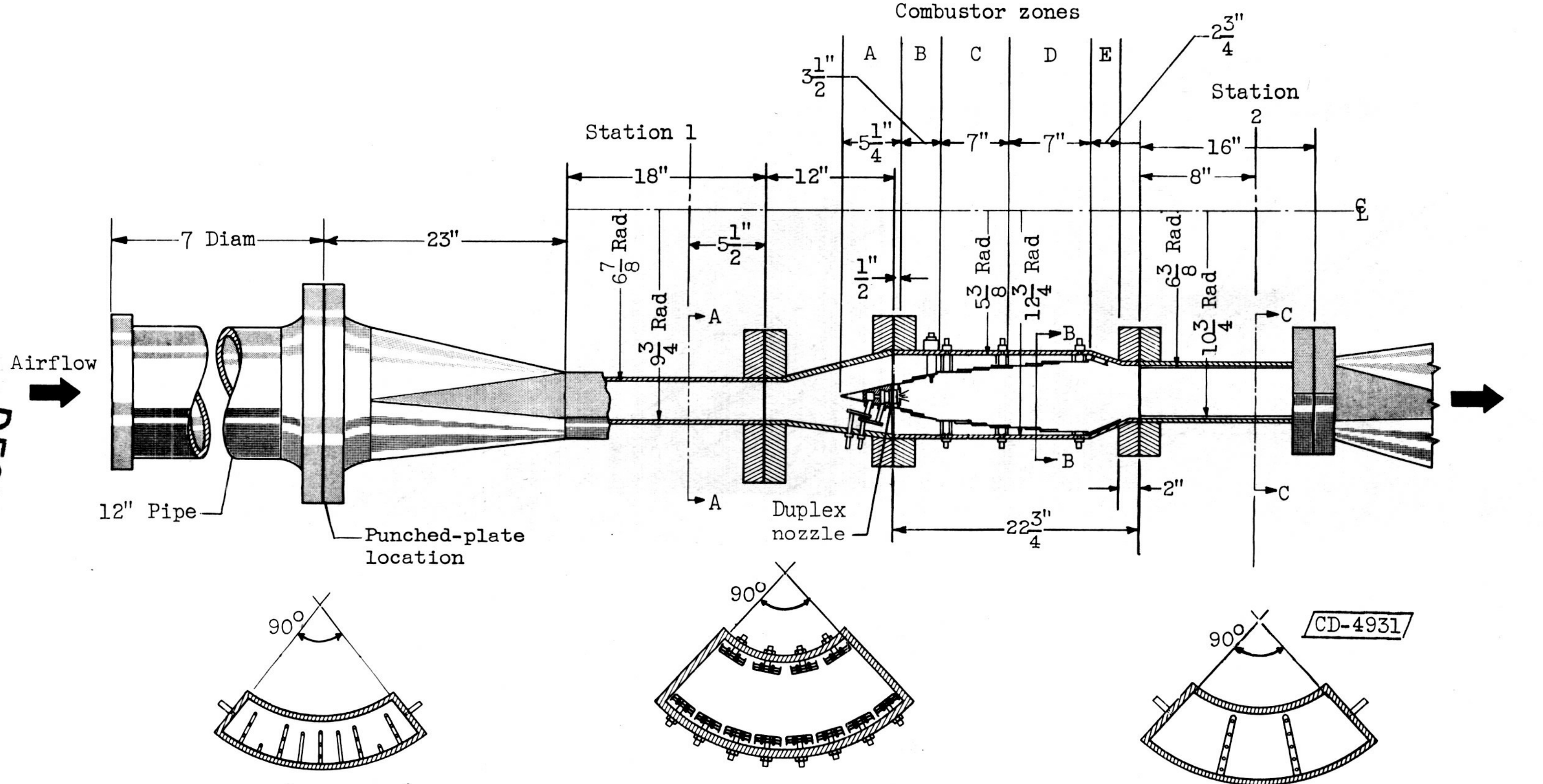


Figure 2. - Direct-fired air heater.



A-A (Station 1)

Inlet-air Chromel-Alumel thermocouples, total-pressure probes, and static-pressure taps. Area, 0.26 sq ft.

B-B

Combustor housing. Cross-sectional area of 0.7288 sq ft used as combustor-inlet reference area.

C-C (Station 2)

Exhaust-gas static-pressure taps and control thermocouples. Also station of polar-coordinate survey system for measurement of exhaust-gas temperature and total pressure. Area, 0.404 sq ft.

Figure 3. - Combustor with inlet and outlet instrumentation sections, showing stations of measurement.

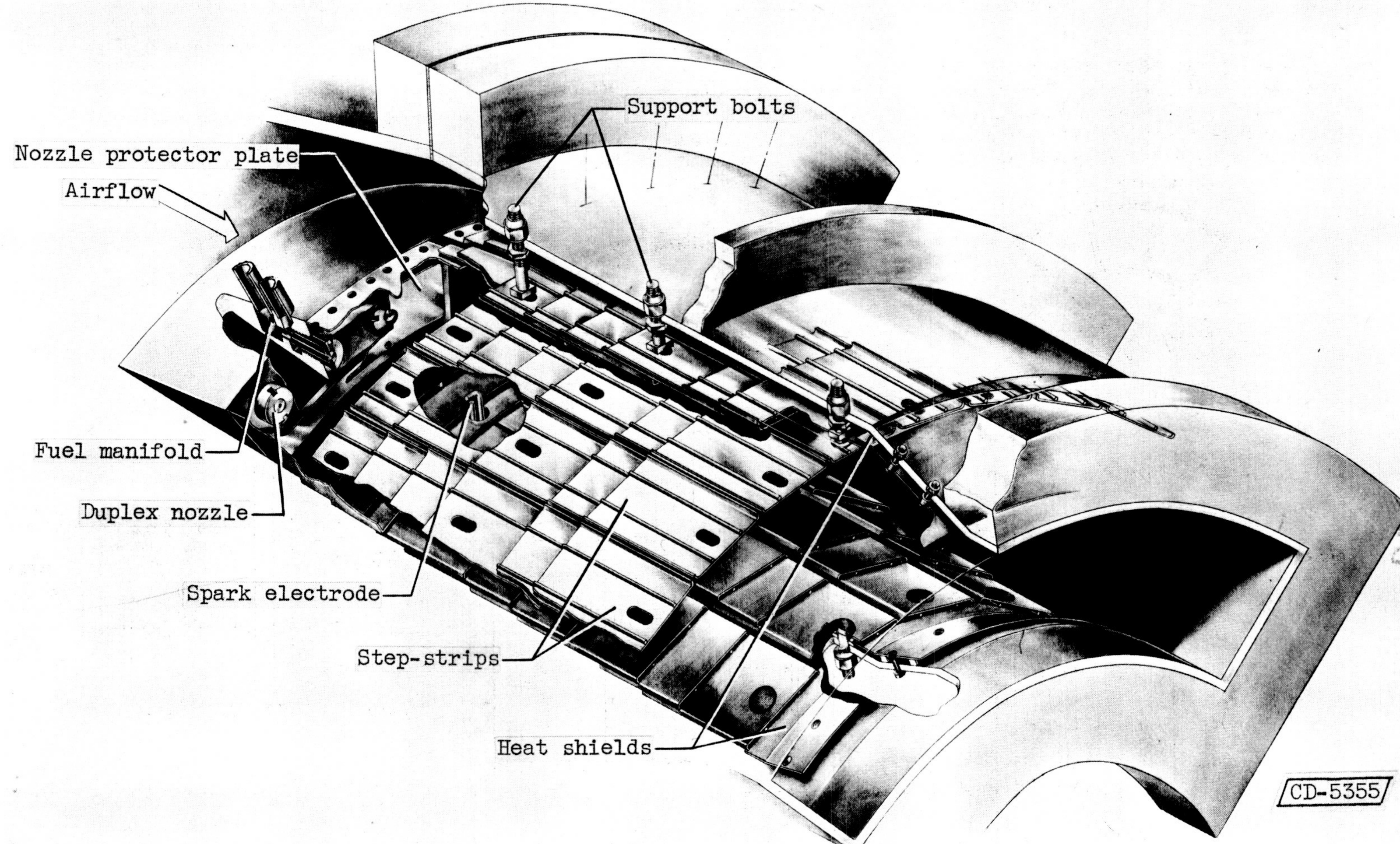
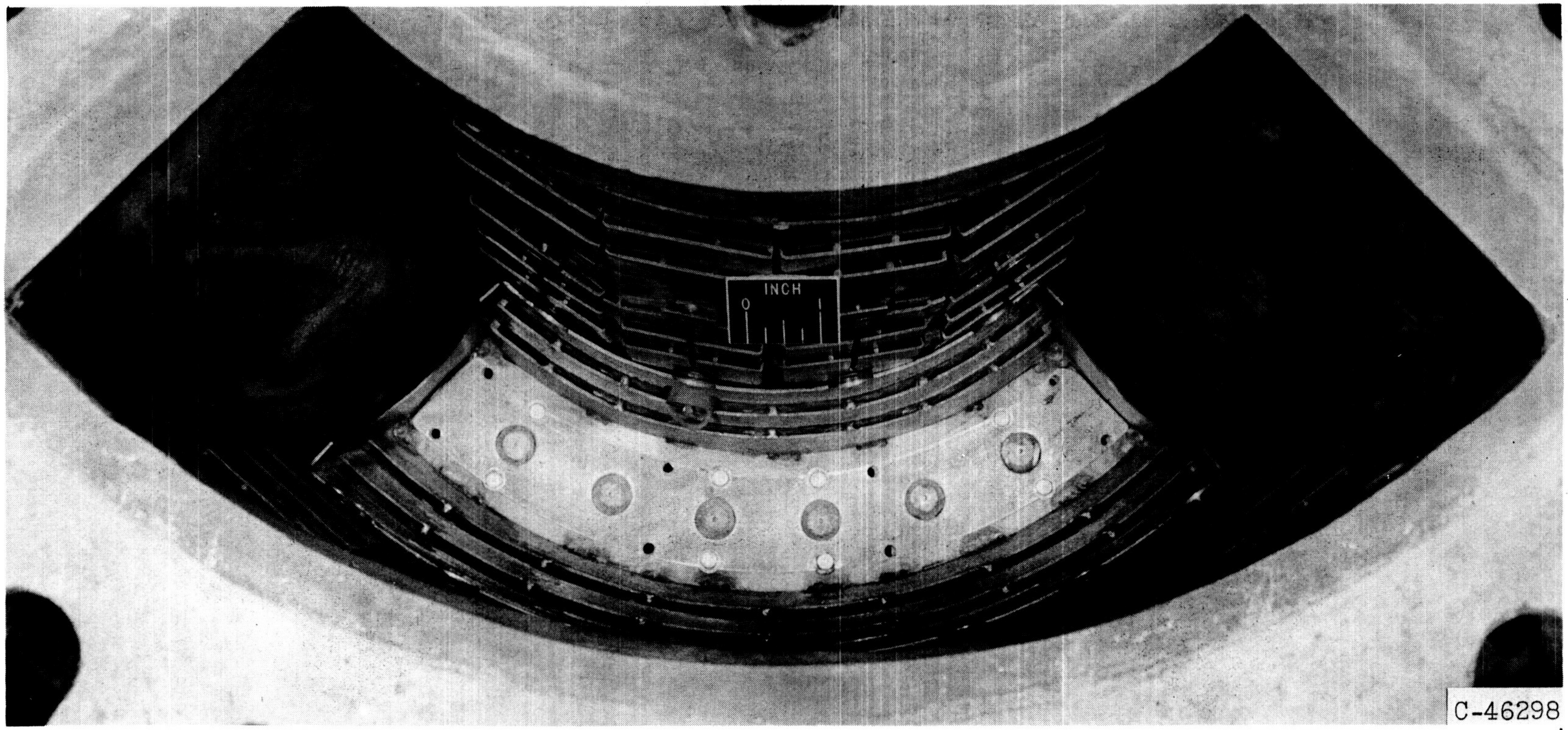
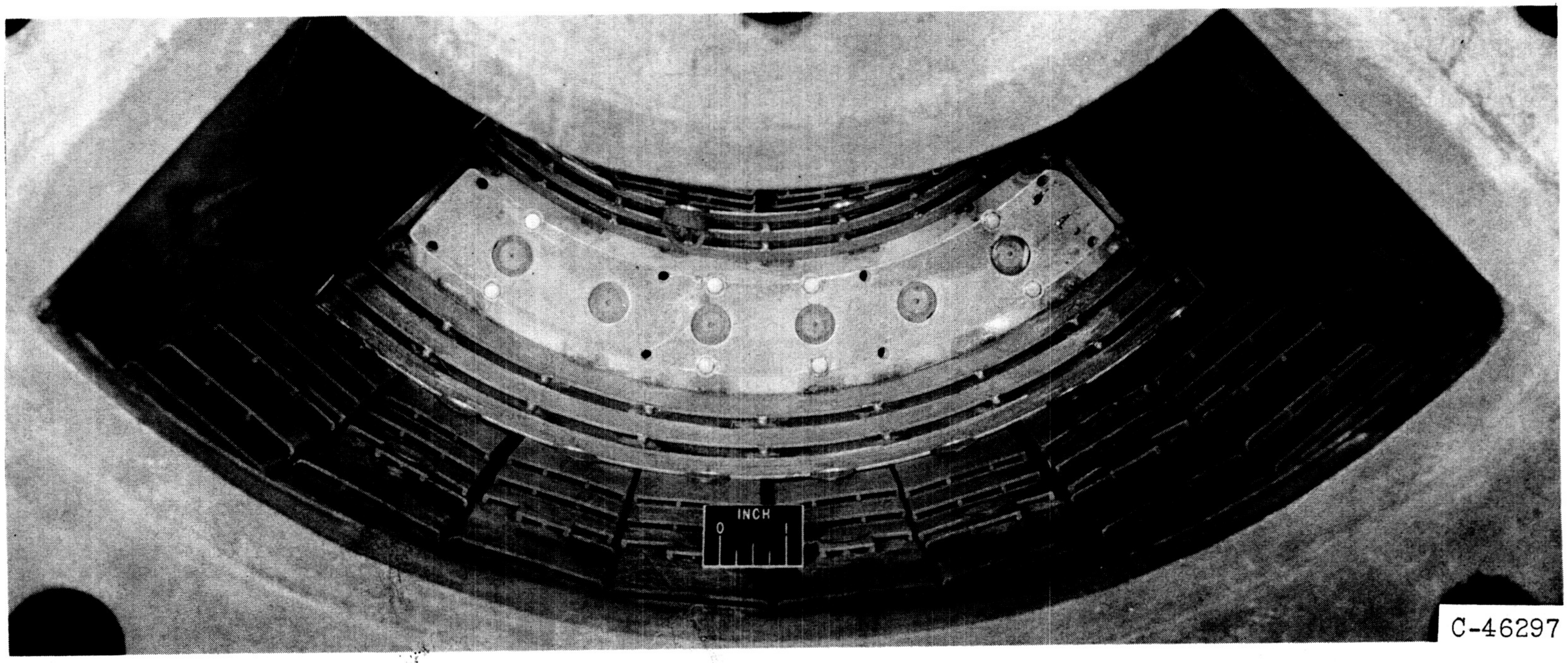


Figure ~~4~~ 3. - ~~Cutaway drawing~~ One-quarter sector of ~~test~~ SEGMENTED combustor.



(a) Pilot section and short-radius or top channels.

Figure 5. - Pilot section and channels in housing, showing condition before start of test program. View looking upstream toward fuel nozzles.



(b) Pilot section and long-radius or bottom channels.

Figure 5. - Concluded. Pilot section and channels in housing, showing condition before start of test program. View looking upstream toward fuel nozzles.

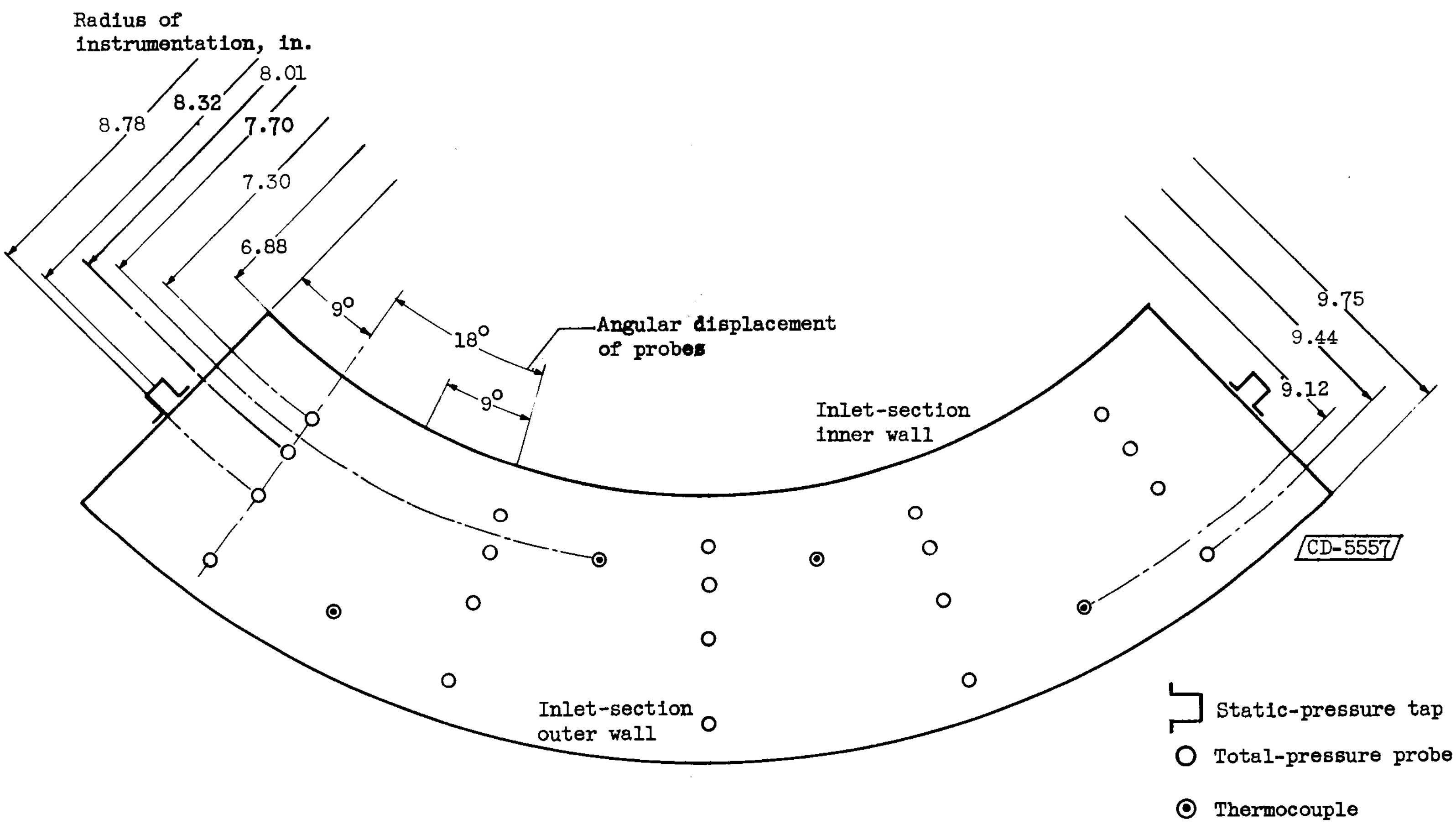


Figure 6. - Cross section of inlet-air instrumentation section (station 1, fig. 3), showing location of temperature- and pressure-measuring probes at centers of equal areas and static-pressure taps.

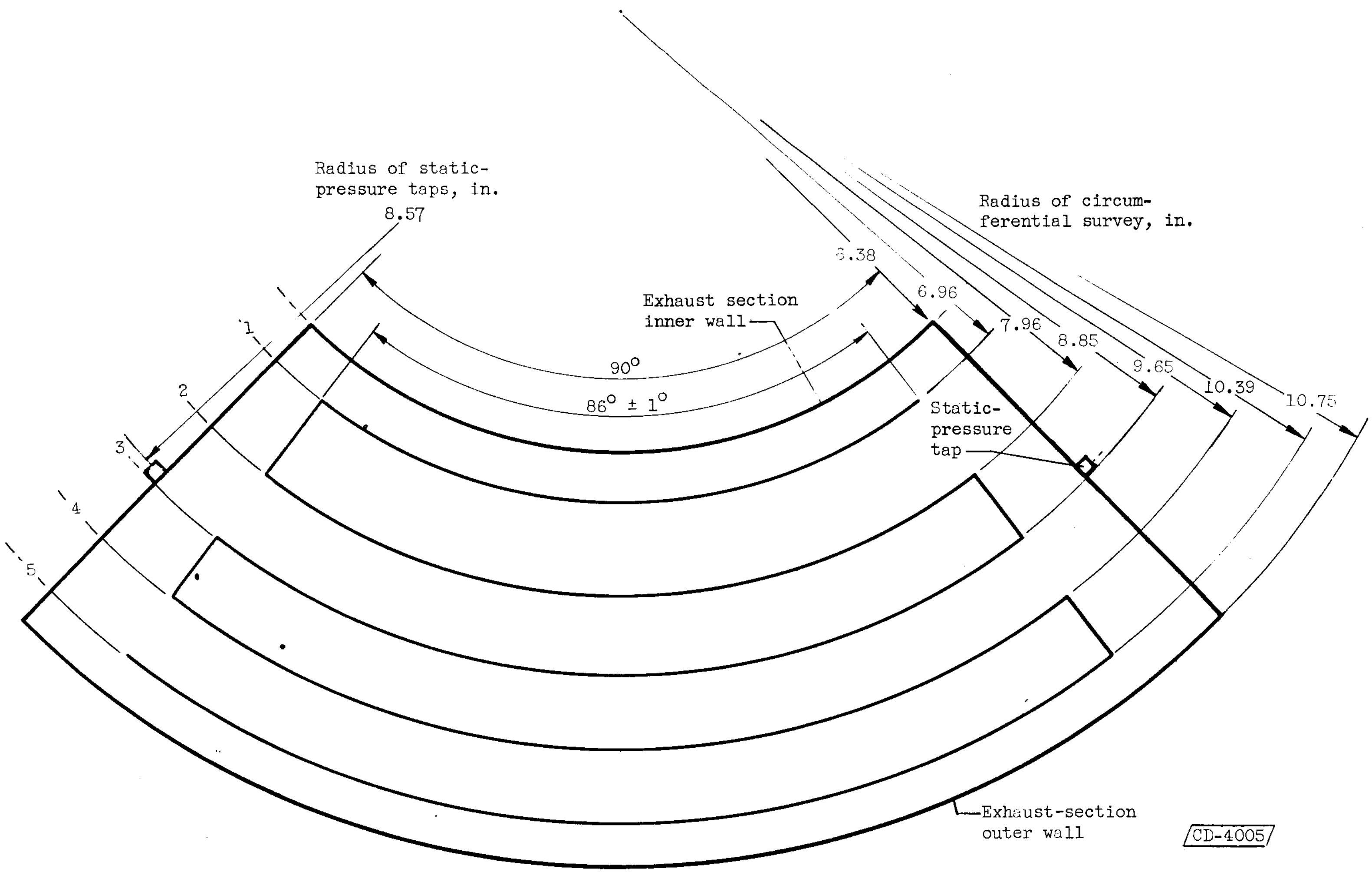
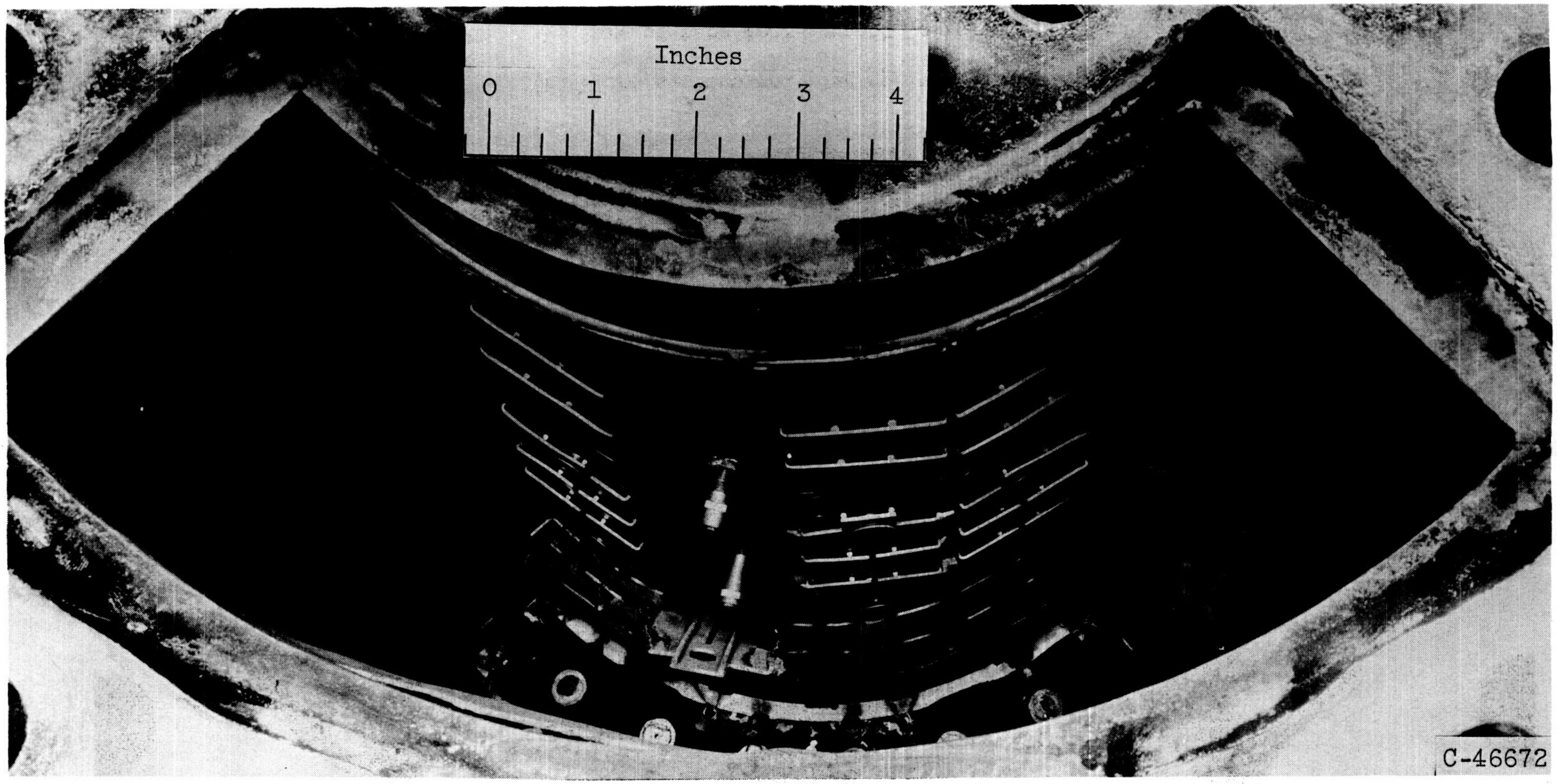
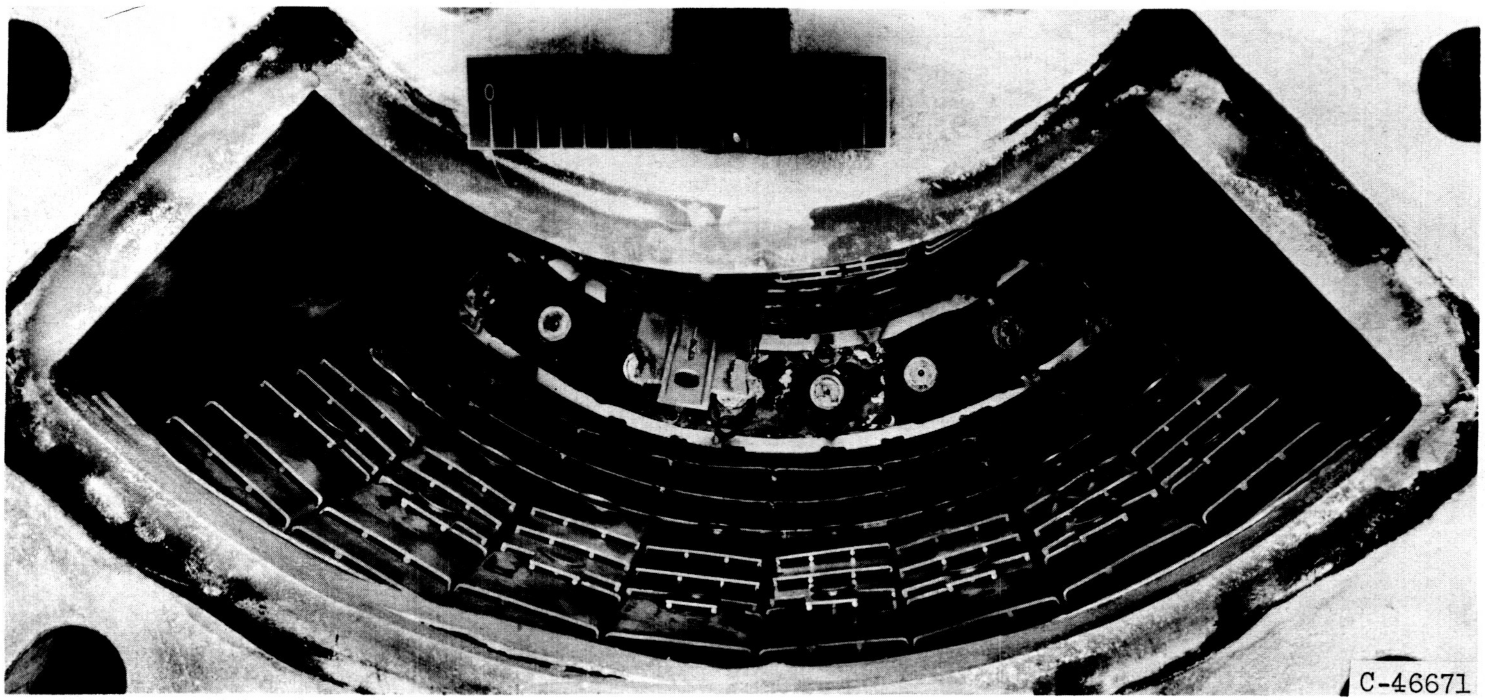


Figure 7. - Paths of probe tips of polar-coordinate survey system across combustor-outlet section (station 2, fig. 3), showing circumferential sweeps at five radii at centers of equal areas for measuring temperatures and total pressures. View looking downstream.



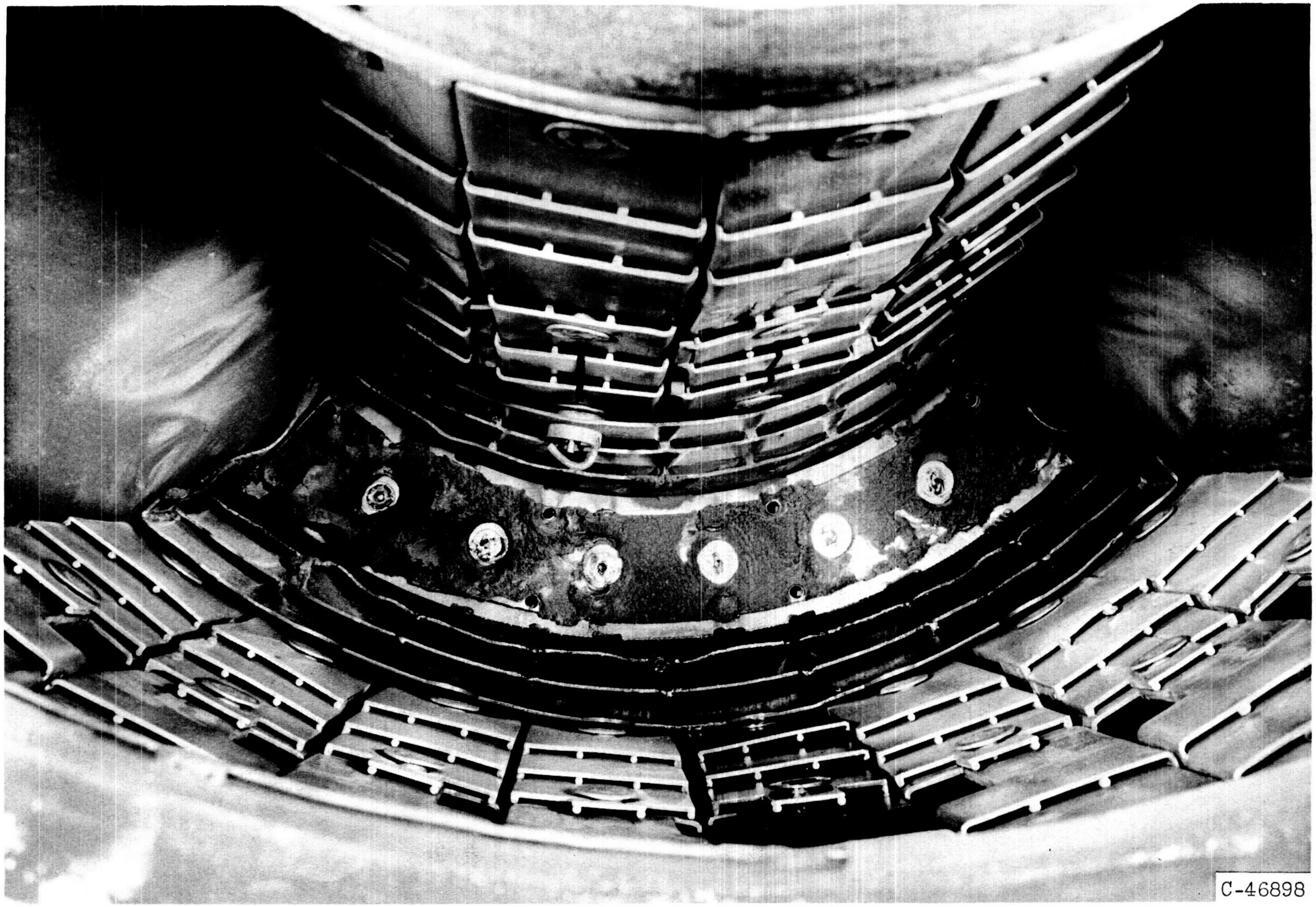
(a) Short-radius channels.

Figure 8. - Failure of tabs from support bolts in second and third rows. Total run time, 9.7 hours.



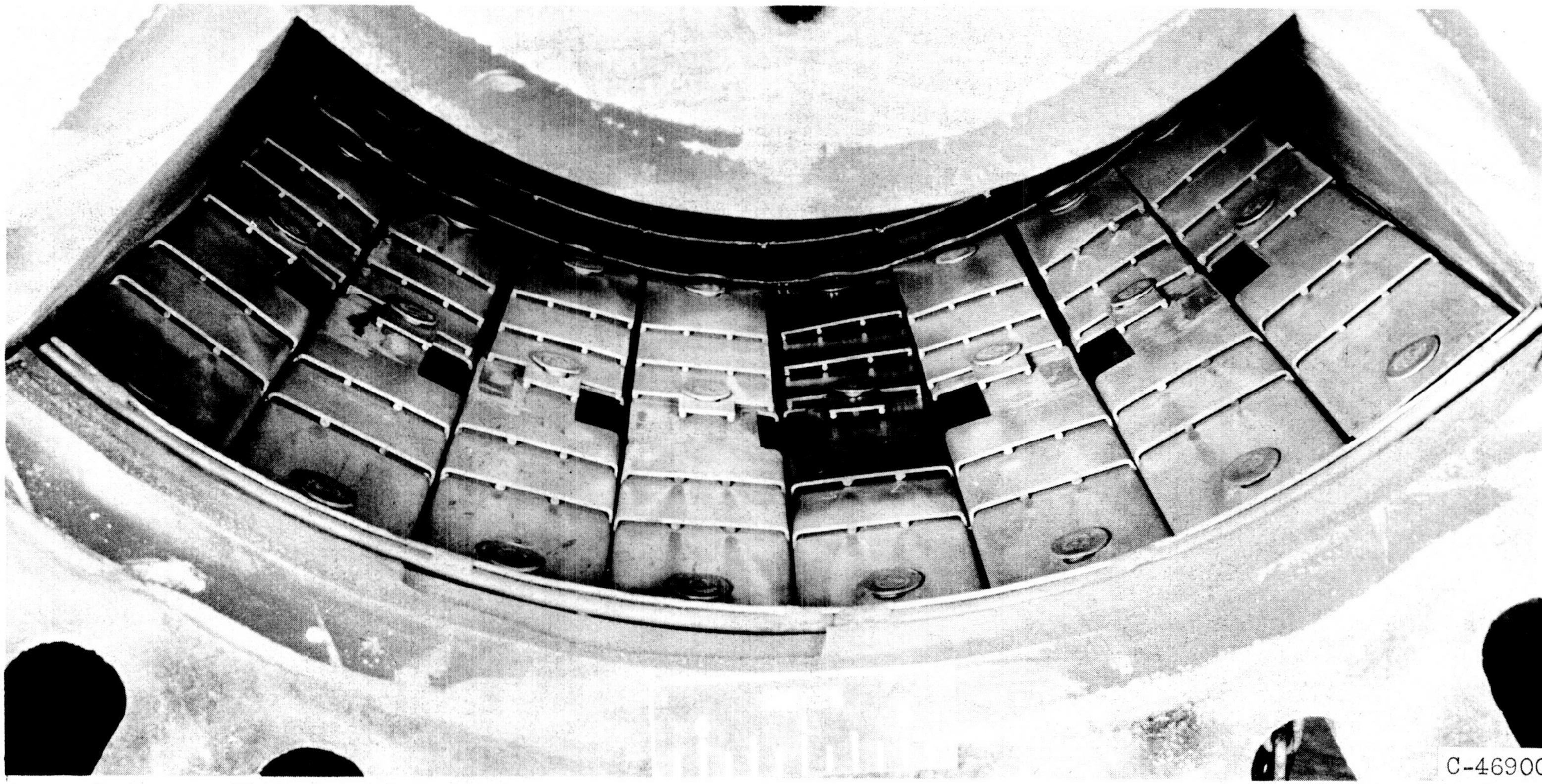
(b) Pilot section and long-radius channels.

Figure 8. - Concluded. Failure of tabs from support bolts in second and third rows. Total run time, 9.7 hours.



(a) Short-radius channels, pilot section, and coke deposits.

Figure 9. - Warped steps of pilot section, excess clearance between pilot section and channels, and coke deposits. Total run time, 20.7 hours.

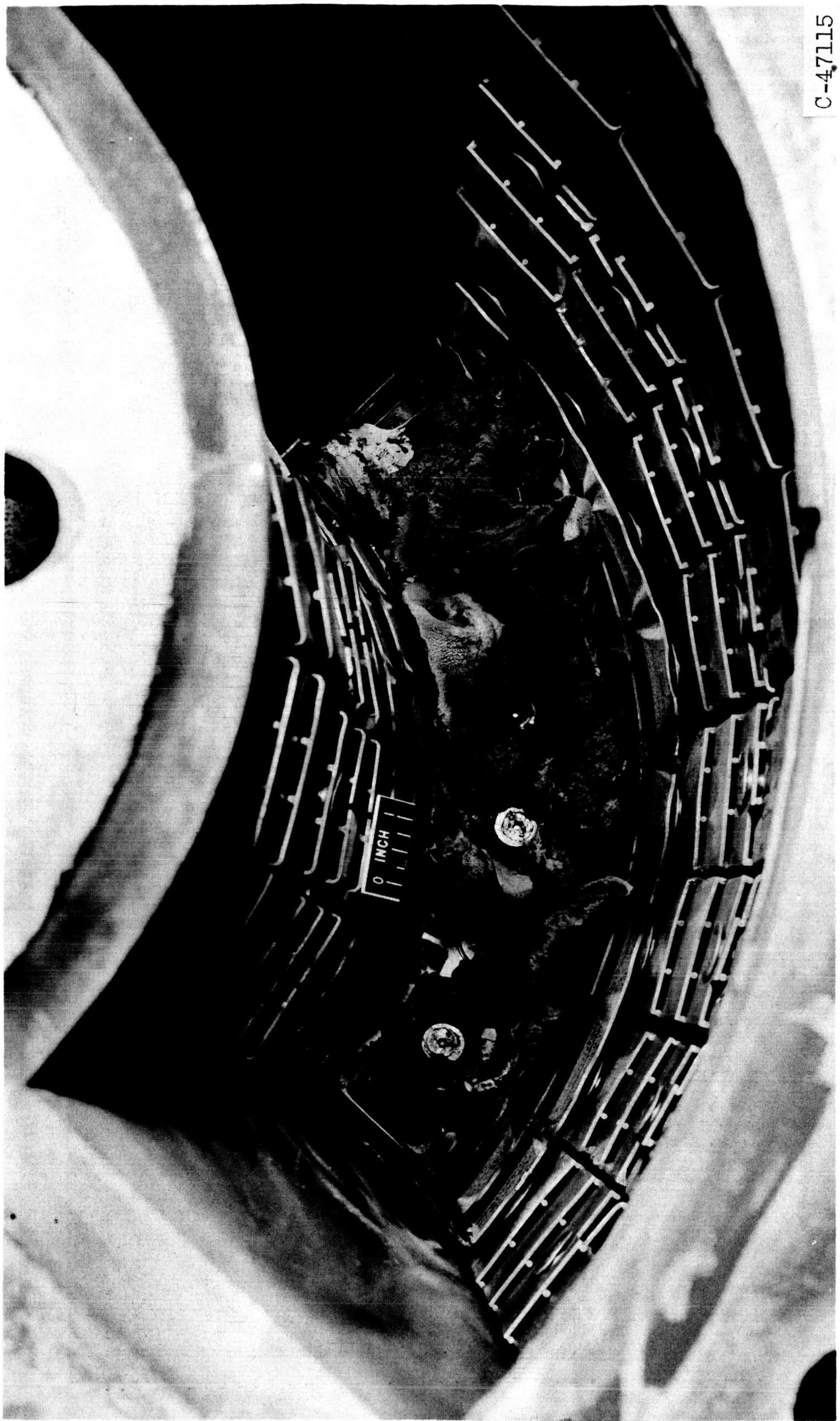


(b) Long-radius channels.

Figure 9. - Concluded. Warped steps of pilot section, excess clearance between pilot section and channels, and coke deposits. Total run time, 20.7 hours.

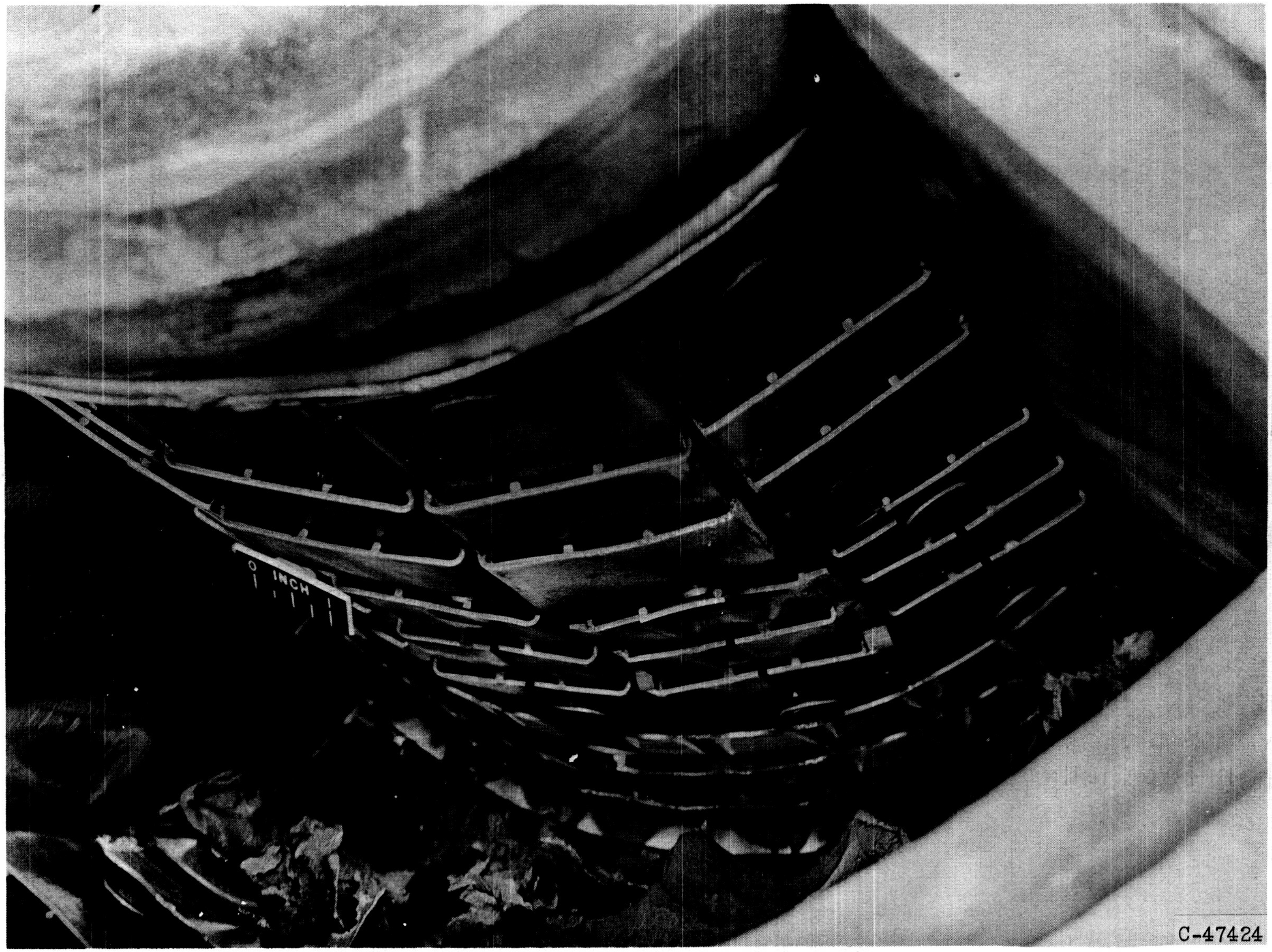
(a) Short-radius channels and pilot section.

Figure 10. - Warped short-radius channel and coke deposits in pilot section. Total run time, 30.4 hours.



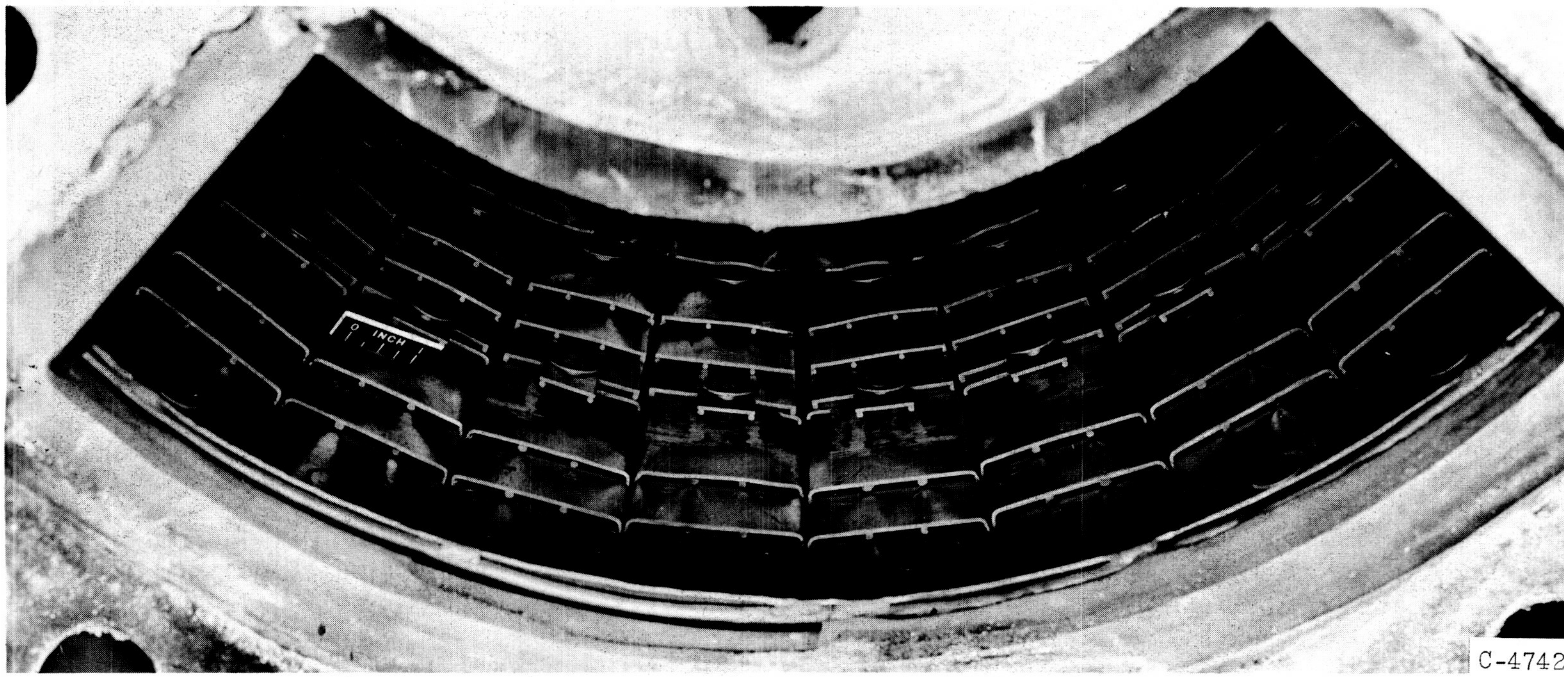
(b) Long-radius channels and pilot section.

Figure 10. - Concluded. Warped short-radius channel and coke deposits in pilot section. Total run time, 30.4 hours.



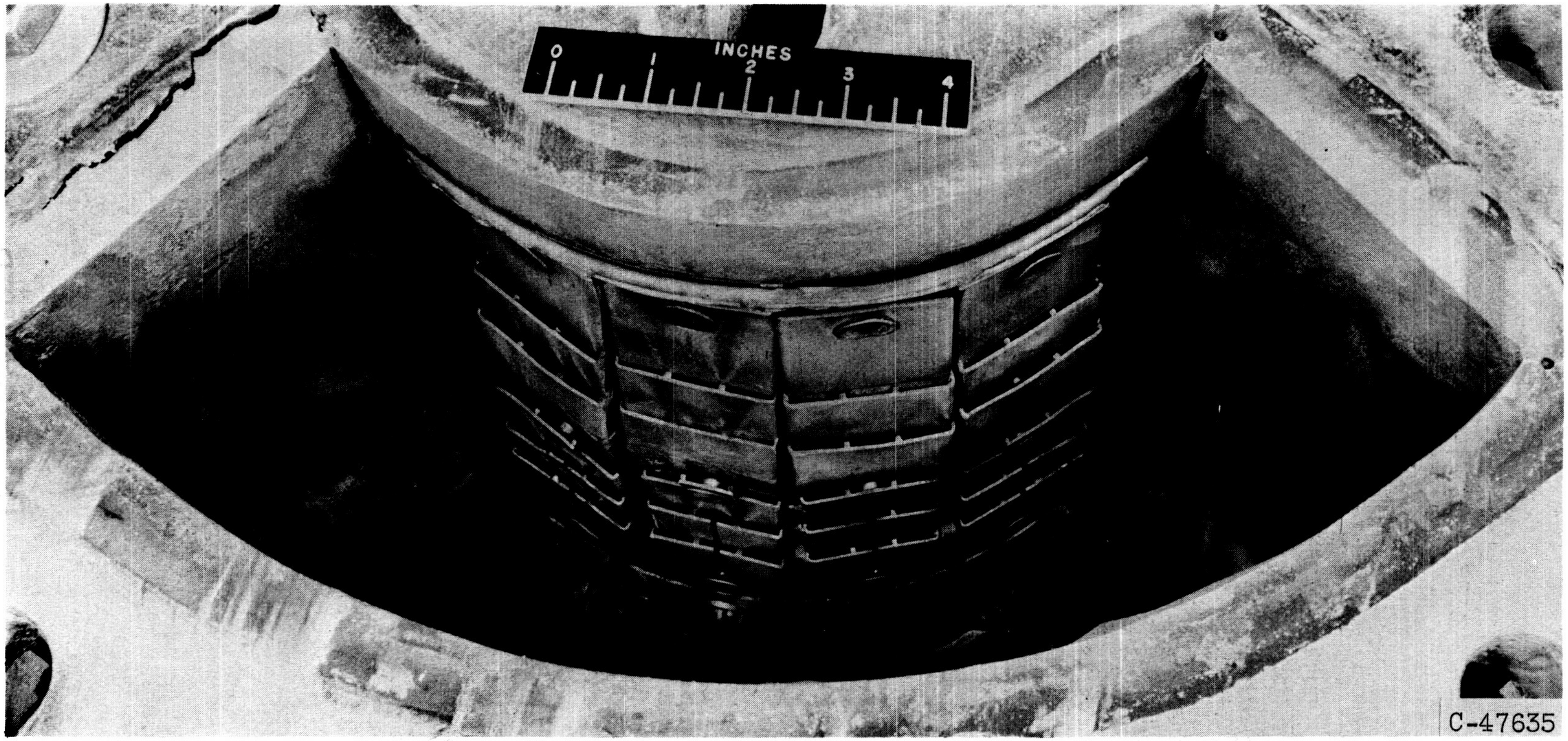
(a) Short-radius channels and coke deposits.

Figure 11. - Warped short-radius channels and coke deposits in pilot section. Total run time, 38.2 hours.



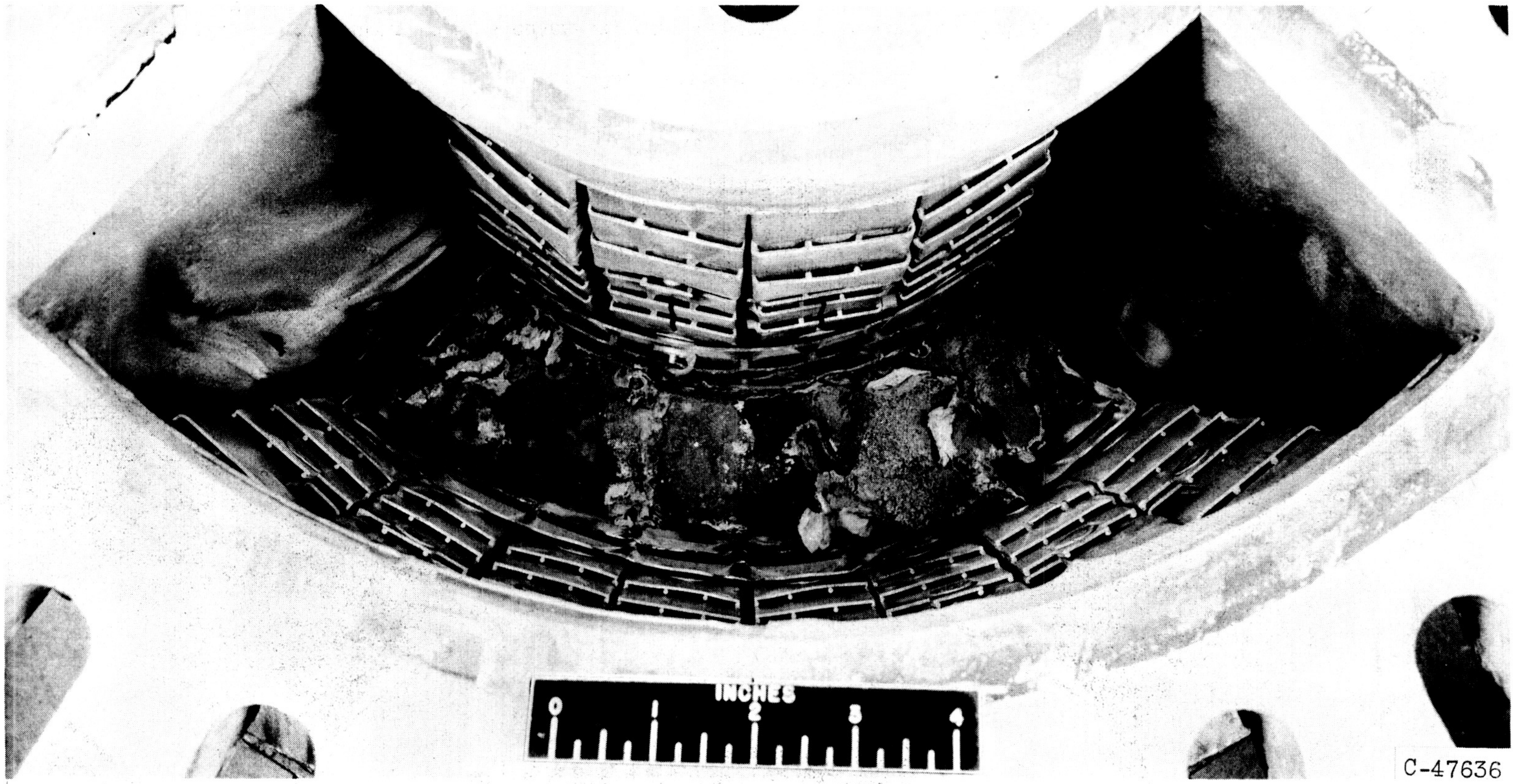
(b) Long-radius channels.

Figure 11. - Concluded. Warped short-radius channels and coke deposits in pilot section. Total run time, 38.2 hours.



(a) Short-radius channels.

Figure 12. - Warped short-radius channels, coke deposits, and warped pilot-section steps. Run time, 41.2 hours.



(b) Pilot-section coke deposits.

Figure 12. - Continued. Warped short-radius channels, coke deposits, and warped pilot-section steps. Run time, 41.2 hours.

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(c) Long-radius channels and pilot section after removal of coke deposits.

Figure 12. - Concluded. Warped short-radius channels, coke deposits, and warped pilot-section steps. Run time, 41.2 hours.

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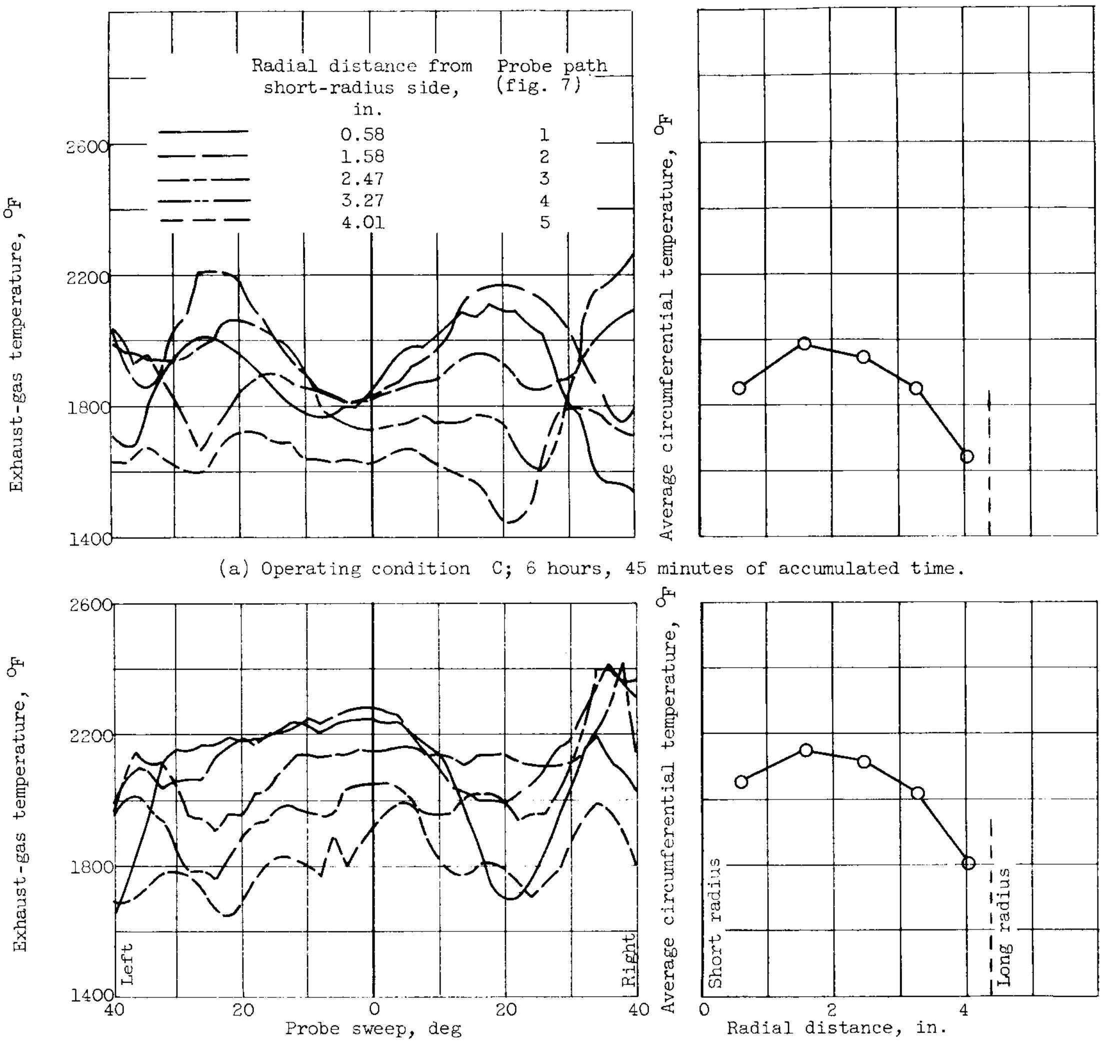

(a) Operating condition C; 6 hours, 45 minutes of accumulated time.

(b) Operating condition F; 19 hours, 45 minutes of accumulated time.

Figure 13. - Exhaust-gas temperature patterns obtained at two different operating conditions. View looking downstream.

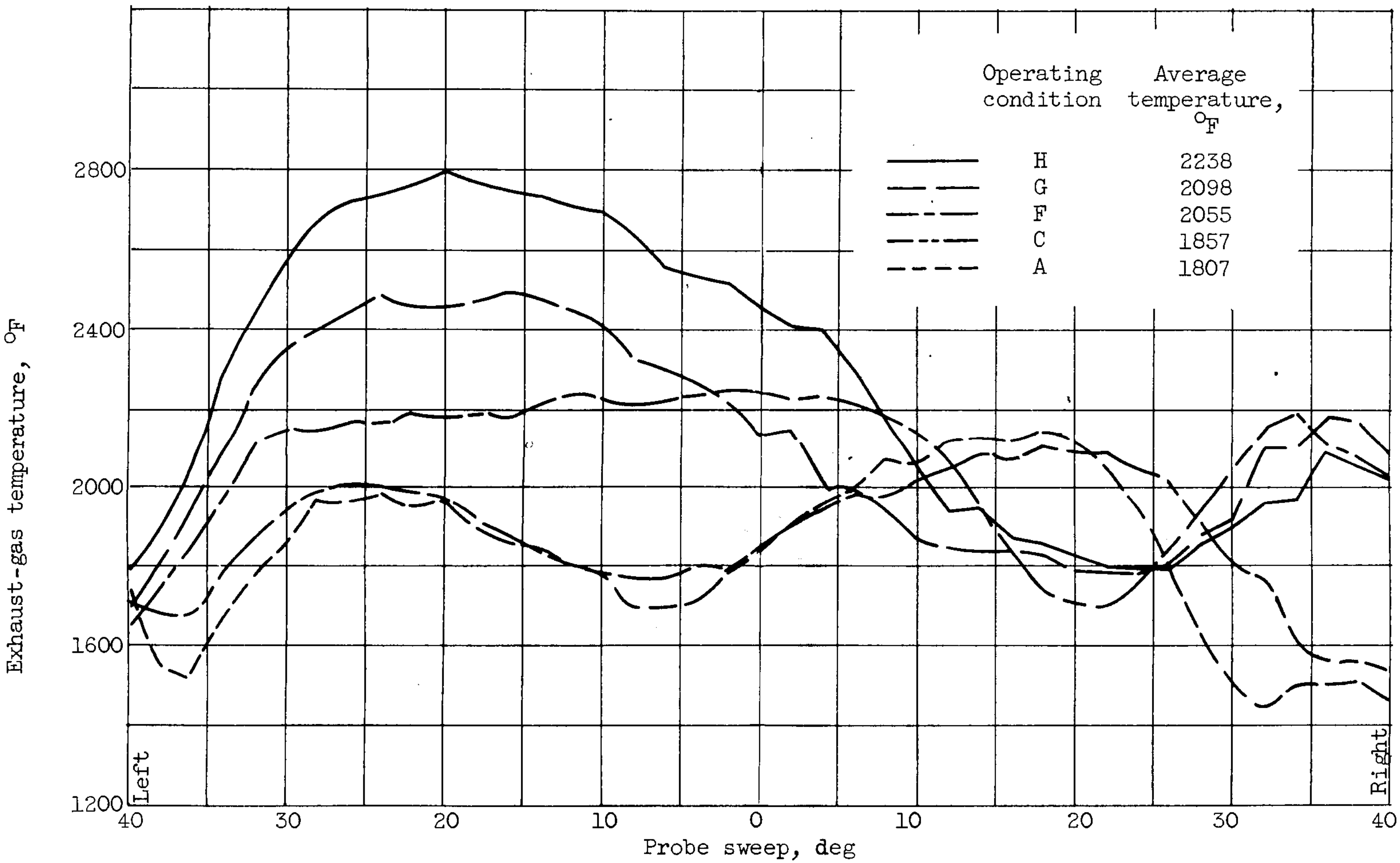

Figure 14. - Exhaust-gas temperature patterns of probe path 1 (fig. 7) for several operating conditions. View looking downstream.

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